

A COMPARISON OF INFLATABLE AND SEMI-RIGID DEPLOYABLE AERODYNAMIC DECELERATORS FOR FUTURE AEROCAPTURE AND ENTRY MISSIONS



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Agility to Innovate, Strength to Deliver



Ball Aerospace
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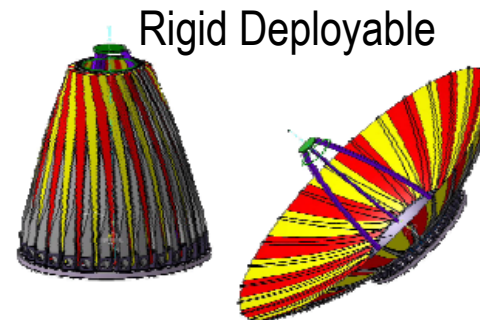
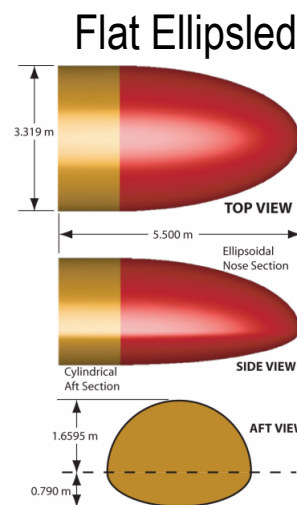
- **Current state-of-the-art**
 - Mars Exploration Rovers and Mars Phoenix Lander
 - ❖ Landing altitude = -1.4 km MOLA
 - ❖ Entry mass = 1000 kg (590 kg payload)
 - Soon to be Mars Science Laboratory
 - ❖ Landing altitude = +2.0 km MOLA
 - ❖ Entry mass = 3000 kg (800 kg payload)
 - ❖ Guided entry with ~20 km x 8 km landing ellipse
- **Deployable aeroshells will need to have equivalent or better performance**
- **This study:**
 - Draws on the results of the High Mass Mars Entry Systems (HMMES) study results
 - Uses the EDL-SA evaluation criteria
 - Compares deployable entry systems using



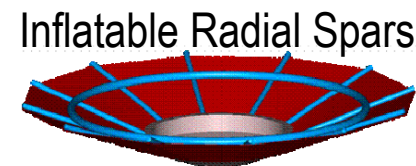
HMMES Study

- Started with multiple configuration options
- Narrowed to the configurations shown below using the evaluation criteria below
 - Data and configurations from literature

Evaluation Criteria	Weighting Factor (Normalized)
Potential for developing L/D	0.18
Scalability to large sizes	0.13
Entry system mass fraction	0.24
Usable payload volume	0.13
Ease of design & construction	0.13
Reliability & durability	0.18



Semi-Rigid Deployable



Tension Cone



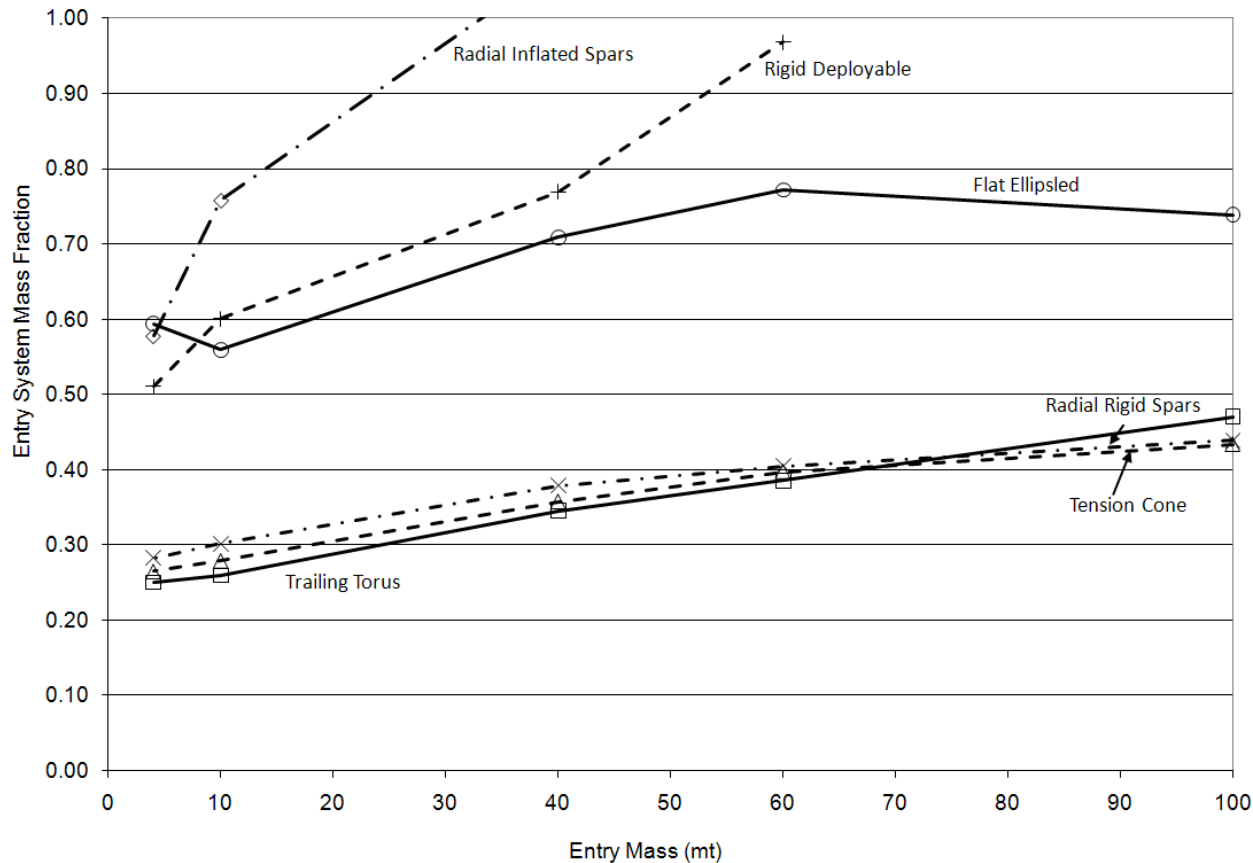
Trailing Torus





HMMES Results

- Direct entry results shown (aerocapture followed by entry has same trends)
 - Entry velocity 7,500 m/s
 - Optimized results are shown for each configuration
- Three configurations are clearly superior, and nearly equivalent in mass efficiency





Comparison of Deployable Configurations

- Compare best 3 configurations from the HMMES study and the stacked torus as used in the EDL-SA study
 - Tension Cone (TC)
 - Trailing Torus (TT)
 - Rigid Radial Spars (RRS)
 - Stacked Torus (ST)
- Use the Analytic Hierarchy Process (AHP) with top-level categories and weights from the EDL-SA study
 - Safety & Mission Assurance (0.35)
 - Affordability & LCC (0.25)
 - Performance & Effectiveness (0.22)
 - Programmatic Risk (0.13)
 - Applicability to Other Missions (0.05)
- Criteria and weights chosen by NASA program managers
- Lower-level criteria modified to suit entry systems rather than architectures



AHP Evaluation Criteria & Weights



Scale For AHP Comparisons

1	Insignificant difference
3	Slight improvement/advantage
5	Significant improvement/advantage



Safety & Mission Assurance Rankings

Configuration	Abort & Reduncancy	# Mars Config Changes	# System Risks	Total Rank
Rigid Radial Spars	0.56	0.50	0.50	0.52
Trailing Torus	0.10	0.17	0.17	0.14
Tension Cone	0.10	0.17	0.17	0.14
Stacked Torus	0.25	0.17	0.17	0.20

- RRS can be deployed early (even prior to Earth-orbit departure)
 - Allows additional abort option (don't depart)
 - Fewer configuration changes at Mars
 - No re-inflation between aerocapture and entry
- ST is slightly better than TT or TC due to redundant inflatable compartments
- RRS is more resistant to micro-meteoroid impacts since it doesn't rely on being air-tight
 - Large impacts would disable any configuration



Affordability & LCC Rankings

Configuration	Cost to TRL6	Cost from TRL6 to 8	EDL-Related LCC			Total Rank
			Entry System Mass Fraction	Stowed Size of Entry System	Complexity of EDL System	
Rigid Radial Spars	0.25	0.38	0.35	0.07	0.25	0.28
Trailing Torus	0.10	0.13	0.19	0.39	0.25	0.17
Tension Cone	0.10	0.13	0.35	0.39	0.25	0.18
Stacked Torus	0.56	0.38	0.11	0.15	0.25	0.37

- **Primary advantage of the ST configuration is the complete sub-orbital test flight**
 - All require some flexible TPS development
 - RRS has a test article ready for flight, but launch vehicle failed
 - TC and TT configurations are still paper studies and require additional development of very large diameter braiding machines or techniques
- **LCC costs**
 - Entry system mass fractions rely on HMMES study and EDL-SA study data
 - Stowed size is the worst for the RRS configuration
 - Complexity is equivalent for all configurations



Performance & Effectiveness Rankings

Configuration	Entry System Mass Fraction	Precision Landing		Total Rank
		Lift Generation	Wind Drift	
Rigid Radial Spars	0.35	0.56	0.38	0.41
Trailing Torus	0.19	0.10	0.13	0.15
Tension Cone	0.35	0.10	0.13	0.23
Stacked Torus	0.11	0.25	0.38	0.21

- Entry system mass fraction is from HMMES and EDL-SA studies
- Precision landing capability
 - Wind drift
 - ❖ Lower ballistic coefficient leads to lower wind drift
 - Lift generation
 - ❖ RRS configuration shape can be directly manipulated via geometry or support mass shift
 - ❖ ST configuration can support some geometry manipulation and limited mass shift
 - ❖ TT and TC configurations are difficult to skew, and their low stiffness supports very little mass shift



Programmatic Risk Rankings

Configuration	Level of EDL SystemMaturity	TRLs of Req'd Technologies	R&D ³ Score of Req'd Technologies	# of Config. Changes Req'd	Total Rank
Rigid Radial Spars	0.25	0.25	0.38	0.50	0.34
Trailing Torus	0.10	0.10	0.13	0.17	0.12
Tension Cone	0.10	0.10	0.13	0.17	0.12
Stacked Torus	0.56	0.56	0.38	0.17	0.42

- **System Maturity and TRL of required technologies**
 - ST configuration has been flow
 - RRS has a flight article ready to go
 - TC and TT are paper studies, and require larger braiding technology
- **R&D3 scores**
 - RRS and ST configurations ranked equal since both are dominated by flexible TPS development
 - TT and TC have additional work in braiding technology development
- **The number of configuration changes is the lowest for the RRS configuration due to the potential for early deployment and no re-inflation between aerocapture and entry, and the same for the inflatable configurations**



Applicability to Other Missions Rankings

- **All configurations ranked equivalent**
 - Data exists to show applicability of deployables to other destinations
 - No data exists showing that any configuration is more suitable than another



Overall Rankings & Conclusions

Configuration	Overall Ranking	AHP Score
Rigid Radial Spars	1	0.40
Stacked Torus	2	0.27
Tension Cone	3	0.18
Trailing Torus	4	0.15

- Rigid Radial Spars configuration is ranked highest overall
 - Difference between RRS and ST was never more than a 3 (slight advantage)
 - RRS ranked highest in the most heavily weighted categories
- TC and TT configurations ranked lowest
 - Primarily due to lack of redundancy and less mature designs
- Final rankings relatively insensitive to change in individual evaluation criteria
- Large difference between RRS and ST configurations
 - If EDL-SA study were re-evaluated with RRS (instead of ST), would its architecture rankings change?
 - Would rigid aeroshells still be the best choice?

Questions?

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